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International Trade, Technological Innovation and Renewable Energy Consumption in Saudi Arabia: An Empirical Analysis Using the ARDL Model

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***Abstract*:**
This study examines the impact of international trade and technological innovation on renewable energy consumption in Saudi Arabia. Using the following key variables: renewable energy, international trade, technological innovation, non-renewable energy, and CO2 emissions, the study applies the ARDL (Auto Regressive Distributed Lag) model over a long period from 1992 to 2023. The results show that international trade has a positive effect but with a one-year lag. In the short term, renewable energy consumption is primarily influenced by its lagged values. In the long term, technological innovation plays a significant positive role in promoting the increase in renewable energy consumption. These results highlight the importance of policies that encourage technological innovation and international trade to boost renewable energy consumption.
***Keywords*:** *renewable energy, international trade, technological innovation, non-renewable energy, CO2, ARDL*

1. INTRODUCTION

Since the the 1970s oil crises, the World Trade Organization has highlighted the close links between international trade, natural resource management and environmental degradation. In this regard, renewable energies have emerged as a central lever in the fight against climate change. Recent literature shows that trade expansion can accelerate the adoption of green technologies, while technological progress improves their efficiency and competitiveness. Bilan et al. (2019) point out that global energy demand is strongly conditioned by these two complementary dynamics.

This line of thought has taken on particular resonance in Saudi Arabia, the world's leading crude oil exporter and a pillar of global energy markets. In 2022, Saudi Aramco produced an average of 10.57 million barrels per day and generated USD 161 billion net income, a record that represents a 46.5% increase on 2021 (Saudi Aramco Annual Report, 2022). This performance is underpinned by an advanced oil infrastructure, a mature export network and high energy prices, giving the kingdom a strategic position but also a marked dependence on crude oil (IEA, 2023). At the same time, domestic energy consumption remains one of the highest in the world: nearly 90% of national needs are still covered by hydrocarbons (IEA, 2022), which can be attributed to a rapidly growing population (estimated at 36 million in 2023, according to the World Bank), urbanization exceeding 84% (World Bank, 2022), and sustained industrialization, particularly in the petrochemical and construction materials sectors.

Aware of the limits of a fossil fuel-based model, the Saudi government has launched the 2030 Vision program, which sets the ambitious target of 58.7 GW of installed renewable capacity by the end of the decade, mainly in solar (40 GW) and wind (16 GW) (Saudi Vision 2030 - Ministry of Energy, 2020). This energy transition is supported by major national projects such as the Sakaka solar power plant (300 MW, commissioned in 2021) and the Dumat Al Jandal wind farm (400 MW, operational since 2022) (ACWA Power, 2022; MEIM, 2023).

In this dual movement of trade openness and technological change, the question arises as to the exact role played by international trade and innovation in the spread of clean energy. In order to provide an empirical answer, this paper examines the relationship between international trade, technological innovation and renewable energy consumption in Saudi Arabia over the 1992-2023 period. Using the ARDL model, it seeks to measure the magnitude and timing of these effects, while taking into account the persistent place of non-renewable energies and CO_2 emissions.

The article is organized as follows: section 2 reviews the theoretical and empirical literature on the links between trade, innovation and renewable energies; section 3 describes the methodology and data; section 4 presents the econometric results; finally, section 5 discusses the implications of these results and proposes recommendations for Saudi public policies on sustainable energy transition.

2. LITERATURE REVIEW

2.1 International trade and renewable energy

Current research can be divided into two complementary but distinct streams on the relationship between international trade and renewable resources. On the one hand, there is the traditional view that stresses the risk of trade-induced overexploitation of renewable resources. This perspective highlights concerns about environmental deterioration and biodiversity loss due to unregulated exploitation to meet global demand. On the other hand, another perspective is emerging which sees international trade as a potential lever for the sustainable management of renewable energies. This approach encourages the adoption of business practices that favor the preservation and efficient use of natural resources. For example, it argues that international trade can facilitate the specialization of countries in products requiring specific renewable resources, while allowing the import of goods produced in a more environmentally-friendly way. Recent empirical studies use advanced methods such as panel cointegration techniques to explore these complex dynamics. For instance, Lean & Smyth (2010) studied the relationship between international trade and renewable energy consumption during the 1980 to 2008 period in a sample of 11 African countries: Algeria, Comoros, Egypt, Gabon, Ghana, Kenya, Mauritius, Morocco, Sudan, Swaziland and Tunisia. The empirical analysis begins with stationarity tests, followed by panel unit root tests for cointegration, then causality tests and finally long-run estimates. The results of the panel error correction model reveal that there is evidence of bidirectional causality between exports and production and between imports and both in the short and long term. However, in the short term, there is no evidence of causality between trade (exports or imports) and renewable energy consumption, and between production and renewable energy consumption. These findings suggest that in the short term, trade activities do not appear to have a direct impact on renewable energy consumption. In the long term, the estimates show that trade and renewable energy consumption have a statistically significant positive impact on production. This indicates that trade and use of renewable energies could increase production in these countries in the long term. Sadorsky (2012) used panel cointegration regression techniques to examine the relationship between energy consumption, production and international trade in a sample of 7 South American countries during the 1980 to 2007 period. Panel cointegration tests show a long-run relationship between production, capital, labor, energy and exports, and a short-run relationship between production, capital, labor, energy and imports. Short-term dynamics show a bidirectional feedback relationship between energy consumption and exports, production and exports, and production and imports. There is evidence of a short-term unidirectional relationship between energy consumption and imports. In the long term, there is a causal relationship between trade (exports or imports) and energy consumption. These results have implications for energy and environmental policy. An important implication of these results is that environmental policies designed to reduce energy consumption will reduce trade. Environmental policy aimed at reducing energy consumption is therefore at odds with trade policy. Furthermore Turan (2013) examined the complex dynamics between international trade and energy consumption in Singapore from 1960 to 2011 using a bivariate differenced model to demystify the links between these two variables important to the Singaporean economy. The author found different results that show that in Singapore there is a significant long-term relationship between imports and energy consumption. The study points to a unidirectional link between growth in international trade and growth in energy consumption in both the short and long term. This suggests that trade growth in Singapore is driven by growth in energy consumption, which can be interpreted as a dependence of Singapore's trade on the efficient availability and use of energy. These results show that efficient management of energy resources is crucial for Singapore's economic development and international trade. Moreover, Amri (2017) examined how trade and economic growth and renewable energy consumption in developed and developing countries were linked. To study the dynamic interactions between variables over the 1990 to 2012 period, the econometric model used is a VAR model. Its results also revealed a feedback link between international trade and renewable energy consumption, underlining the importance of the interaction between these two factors for overall economic dynamics. In that study, the VAR model is appropriate. The results highlight a feedback link between international trade and renewable energy consumption. This finding concludes to a dynamic interaction between these two factors, where trade activities can affect the adoption of renewable energy sources and vice versa. The importance of considering the energy dimension in international trade and economic growth is underlined by this interrelationship. It is important to note that although both studies examined the correlation between world trade and renewable energy consumption, they found contradictory results. Then, Shakouri & Yazdi (2017) attempted to capture the dynamic links between international trade and renewable and global energy consumption using South African annual data from 1971 to 2015. Through the use of the ARDL (Autoregressive Distributed Lag) bounds testing approach and Granger causality tests, the authors concluded that international trade tools were effective in attributing variations in energy resource consumption in South Africa, as demonstrated by the inverse causal association discovered. Opoku et al (2020) studied this issue, examining the interaction between international trade, renewable energy consumption and environmental quality in Nordic countries over the 2001-2018 period. This study used the unit root test (CIPS) as well as the cross-sectional dependence test (CD) to assess stationarity and diagnose cross-sectional dependence problems, respectively. Moreover, it resorted to a dynamic common correlated effect model (DCCE) to guarantee the robustness of the results. The findings highlight a significant positive correlation between international trade and renewable energy in Nordic countries, while demonstrating that renewable energy consumption contributes to improved environmental quality. Therefore, policies to promote renewable energy can foster both economic growth and environmental sustainability meeting key sustainable development objectives. Innovative approaches, such as the Potential Index of International Trade introduced by Gozgor et al (2020), quantitatively assess the benefits of trade for economic welfare as a function of the share of imports in GDP. Their study reveals that the benefits of international trade are modest in developed economies, but more significant in developing economies. They examined the impact of this index on renewable energy consumption using an unbalanced panel dataset consisting of 36 member countries of the Organisation for Economic Co-operation and Development over the 1966-2016 period. The results highlight a positive correlation between the International Trade Potential Index and renewable energy consumption. In addition, the study found that per capita income, per capita carbon dioxide emissions and energy prices stimulate demand for renewable energy. Banerjee & Kallal (2022) investigated the impact of international trade on renewable energy in data covering 186 countries over a 26-year period, from 1990 to 2015, collected from the World Bank. The method used (IPAT) also known as the IPAT equation, was proposed for the first time. This study uses several variables, including total population GDP per capita and energy intensity, to assess the relationship between trade and renewable energies. Renewable energy consumption is also considered as a measure of environmental impact, alongside trade variables such as trade volume and trade taxes. They have shown that the effects of international trade on renewable energy consumption vary in the short and long term. In the short term, some research has identified no direct causal link between international trade and the use of renewable energies, while in the long term, international trade seems to encourage their adoption, particularly in developing countries. Studying the provincial and regional development in China, Chen et al. (2022) used a dynamic panel model to examine the impact of trade openness on provincial and regional energy intensity. They systematically studied the components of energy intensity, both theoretically and empirically. They assessed the energy intensity of 30 Chinese provinces and regions from 2005 to 2018, and proposed a normative interpretation of the effect of trade openness and economic growth on China's energy intensity. The results show that economic growth and trade openness decrease energy intensity. However, the impact of economic growth on energy intensity is more obvious. Energy intensity is mainly influenced by exports, while the impact of imports is not significant. Then, in order to reduce energy use and manage its evolution, it is essential for the government to be actively involved in trade openness and economic growth. This leads us to propose the following hypothesis:

H1: Development of international trade promotes the growth of renewable energies.

2.2 Technological innovation and renewable energies

Alam & Murad (2020) examined the short- and long-term effects of economic growth, trade openness and technological development on renewable energy use in 25 OECD countries over a 43-year period. The results indicate that technological development, economic growth and trade openness have a significant impact on long-term renewable energy use in these countries in similar ways. They note that the short-term trend is mixed, probably due to the varying levels of trade openness and technological development in OECD countries. Meirun et al (2021) used the Bootstrap Autoregressive Distributed Lag (BARDL) method to analyze the impact of green technological innovation on the Singaporean environment. According to the authors, green technology innovation shows a significant positive correlation with economic growth and a significant negative correlation with carbon emissions. By increasing technological advances, energy efficiency can help to reduce carbon footprints and environmental harms, as observed by Udeagha & Ngepah (2022) in 73 developing countries studied between 1990 and 2016. However, technological advances can encourage a transition from carbon-intensive fossil fuels to renewable energy sources, helping to reduce greenhouse gas emissions.

Technological advances can increase renewable energy supply capacity and optimize the energy mix. Wenlong et al (2022) examined the effect of key factors such as technological advances, energy efficiency, trade openness and institutional quality on environmental quality in 10 Asian economies between 1995 and 2018. These influences were analyzed using advanced econometric techniques, such as cointegration methods, as well as the (CS-ARDL) model. Their empirical study highlights that trade openness and institutional quality have an adverse effect on environmental quality, while technological advances and energy efficiency contribute positively to its improvement. In conclusion, they recommend that Asian economies strengthen the quality of their institutions and increase their investment in innovative technologies. Zhou et al (2023) focused on technology transfer (innovation levels and knowledge sharing) and the influence of green energy consumption (which is measured by the share of energy from renewable sources) on carbon emissions in 39 high-income countries in Europe and Central Asia, such as Albania, Andorra, Armenia, etc., up to 2021. Different analytical methods are used in this study, such as the (GMM) method, quantile regression and the cointegration panel approach. The results indicate that innovation and the use of renewable energies can help reduce carbon emissions, which have a positive impact on the atmosphere. It is essential to transfer technologies to promote innovative, environmentally-friendly solutions, particularly in developing countries, in order to combat climate change. It is therefore essential to encourage the growing use of renewable energies to replace fossil fuels, in order to reduce CO2 emissions. Recently, Jiang et al (2024) studied developed economies between 1989 and 2021. Using green innovation, exports and imports, they studied the impact of environmental R&D spending on carbon emissions from renewable energy consumption. New methods of panel econometric analysis were used in this study. The results indicate that investment in environmental R&D and greener energy is shown to help reduce carbon emissions, suggesting a positive correlation between green innovation and renewable energy consumption. Exports also have an inverse correlation with carbon emissions. Imports, on the other hand, lead to a deterioration in consumption-related carbon emissions, suggesting that they have a negative impact on renewable energy consumption. In this regard, while the study asserts that innovation is positively associated with renewable energy consumption, the relationship between international trade and renewable energy consumption is more complex, particularly where imports are concerned. According to the study, it is suggested that research and development spending be increased by promoting the greening of innovation to promote sustainable development. This leads us to the following hypothesis:

H2: Technological innovation has a significant positive impact on renewable energy consumption.

2.3 International Trade, Technological Innovation and Renewable Energy Consumption

Khan et al. (2020) highlights the crucial importance of international trade, technological innovation, renewable energy consumption and carbon emissions for G7 countries from 1990 to 2017.Their study applied second-generation panel cointegration methodologies, such as the Pesaran and Yamagata (P&Y), the slope heterogeneity test and the Pesaran cross-sectional dependence (CD) test. The findings reveal a stable long-term relationship between trade, CO2 emissions, technological innovation and renewable energy consumption. More specifically, it seems that imports increase consumption-based carbon emissions, while exports, technological innovation and renewable energy consumption help to reduce these emissions. In addition, the Granger causality test indicates that policies targeting exports, imports and technological innovation significantly alter green energy consumption and CO2 emissions. Similarly, Ali et al (2021) examined the role of international trade, technological innovation and renewable energy consumption in the link between international trade, technological innovation and CO2 emissions for the top ten carbon-emitting countries. The results reveal cross-country dependence and slope heterogeneity, phenomena detected by the Pesaran and Yamagata tests. Using Westerlund's cointegration method, the study shows a long-term equilibrium relationship between CO2 emissions and variables such as technological innovation, international trade and renewable energy consumption. Furthermore, the results obtained using the CS-ARDL method indicate that these same factors play a crucial role in explaining carbon emissions, whether consumption- or territory-based. These findings highlight the importance of integrating innovation and renewable energies into business strategies to reduce CO2 emissions. The results show that international trade and innovation are essential to catalyze the transition to renewable energies, which makes a significant contribution to reducing carbon emissions, while highlighting the complexity of economic and environmental interactions between the main emitting countries. Furthermore, Herman and Xiang (2022) examined this issue, and found that international trade plays a key role in transmitting signals of stringency from foreign environmental regulations, generating domestic renewable energy innovation. Examining a sample of 32 countries during a 16-year period, the results gather strong empirical evidence that foreign environmental regulations, when balanced by bilateral trade, have a significant impact on fostering innovation. These results shed further light on the influence of international trade and technological innovation on renewable energy consumption. They show that international trade not only has a direct impact on renewable energy consumption, but also plays a key role in stimulating innovation by being exposed to stringent foreign environmental regulations. In this way, international trade and technological innovation can both be at the forefront of the adoption and development of renewable energies, supporting the idea that these have a significant positive effect on renewable energy consumption.

Recently, Ofori et al (2024) show that international trade and technological innovation have an impact on renewable energy consumption, taking into account economic growth, access to electricity, pollution, industrial restructuring and urbanization. They used information on the MINT (Mexico, Indonesia, Nigeria and Turkey) and BRICS economies during the 1990 to 2020 period. The results reveal that technological innovation has a positive effect on renewable energy consumption in MINT countries, while it has a negative effect in BRICS countries and the overall sample. This suggests that technological innovation may favor renewable energy consumption in some environments, but its impact may be restricted or reversed in others. Furthermore, international trade shows a beneficial effect on renewable energy consumption in the BRICS bloc, while it presents a negative effect in the overall sample and MINT countries. This finding indicates that the impact of international trade and technological innovation on renewable energies may differ according to economic contexts. We therefore propose the following hypothesis:

H3: Technological innovation stimulates the positive impact of international trade on renewable energy consumption.

3. METHODOLOGY

3.1 Model

We constructed the estimation model with reference to Zhang et al. (2022). The model is written as follows:

$$ER_{it} = \beta_0 + \beta_1 ER_{it-1} + \beta_2 IT_{it} + \beta_3 ENR_{it} + \beta_4 INNOV_{it} + \beta_5 CO2_{it} + \mu t \quad (1)$$

In equation (1), ER represents the share of renewable energy consumption in total energy consumption, which is a dependent variable, while the other variables are independent variables: IT refers to international trade, ENR refers to non-renewable energies, INNOV refers to technological innovation, and CO2 represents the carbon dioxide emissions caused by the total energy consumption of country i at a given time t. Table 1 below presents the definition and description of all the variables used in our study, including the dependent variable (renewable energies) and the independent variables (international trade, technological innovation, non-renewable energies, and CO2 emissions).

Table 1. Definition of Variables

Symbol	Variable	Definition	Sources
$\mathbf{RE_{i\,t}}$	Renewable Energy	Renewable energy consumption is the share of renewable energy in total energy consumption.	World Bank
IT	International Trade	It is the sum of exports and imports of goods and services, measured as a percentage of the gross domestic product. Measured by: [(exports + imports) / GDP]	World Bank
$\mathbf{NRE_{it}}$	Non-renewable Energy	Fossil fuels include coal, oil, petroleum products, and natural gas. It is the ratio between fossil fuel consumption and total energy consumption (%).	World Bank
INNOV	Technological Innovation	Patent applications are global patent applications filed under the Patent Cooperation Treaty procedure or with a	World Bank

		national patent office. Measured by Patent Applications per capita	
C02	Carbon dioxide emissions	Carbon dioxide emissions are those that come from the combustion of fossil fuels. Measured in metric tons per capita	World Bank

Our data is collected from: https://databank.worldbank.org/source/world-development-indicators

3.2 Descriptive Analyses

To begin our descriptive analysis, we will explore the central characteristics and variability of the different variables in our model. To this end, we examine the mean, standard deviation, maximum value, and minimum value of each variable. The complete descriptive data are presented in a summarized manner in Table 2 below. We explore the descriptive statistics of the following variables: Renewable Energy (RE), Carbon Dioxide Emissions (CO2), Technological Innovation (INNOV), Non-Renewable Energy (NRE), and International Trade (IT). On average, renewable energies account for 1.68% of total energy consumption in Saudi Arabia. This low proportion indicates that this country still largely depends on fossil fuels, despite some efforts to integrate renewable energy sources into its energy mix. The median value of 0.01 indicates that half of the observations have a proportion of renewable energies less than or equal to this figure. The proportion of renewable energy varies between 1% and 6%; which indicates low variability in the integration of renewable energies, which may reflect structural challenges in these green technologies. The standard deviation of 0.013997 shows a low dispersion around the mean of 1.68%, this low dispersion indicates that levels of renewable energy consumption are relatively stable, which could suggest a slow adoption or constraints in the ability to significantly increase the use of renewable energies. The average annual deviation of CO2 emissions is 0.95%, suggesting that CO2 emissions in Saudi Arabia increase slightly each year, which can be attributed to steady economic growth and persistent dependence on fossil fuels. The annual variations in CO2 emissions range from a decrease of -6.29% to an increase of 6%, this wide fluctuation shows considerable variability in emissions due to variations in economic policies or changes in industrial activities. A standard deviation of 3.24% indicates a relatively high dispersion around the mean; the high dispersion of the data shows significant variability in CO2 emissions from year to year, influenced by oil prices, energy policies, and emission reduction initiatives. The average deviation of technological innovation is 0.197487 or 19.75%, which suggests a general positive trend in the impact of innovations, likely because of technological advancements. The median of 0.096626 suggests that half of the observations have an innovation deviation less than or equal to this figure. The maximum and minimum values are respectively 1.111111 and -0.394737. This indicates a strong fluctuation in the levels of innovation deviation, ranging from -39.47% to 111.11%. The standard deviation rate of 0.332317 is quite high, indicating a strong dispersion of data around the average; the deviations in technological innovation vary considerably. On average, 99.85% of energy consumption in Saudi Arabia comes from non-renewable sources. A strong dependence on non-renewable energy reflects the predominance of natural gas and oil in the country's energy mix, which is one of the largest producers and exporters of oil in the world. The median of 99.99%, very close to 100%, suggests that almost all the studied periods have energy consumption dominated by non-renewable sources. The maximum and minimum values are respectively 99.99678% and 99.12536%. This indicates a very low level of non-renewable energy proportion, with values very close to 100%. This may be due to economic, technical, or political constraints that limit the development of alternative energy sources. The standard deviation of 0.287920 is quite low, which suggests that there is a low dispersion of the data around the mean. On average, international trade represents 71.27% of GDP, which highlights the importance of Saudi Arabia's exports, particularly in the oil sector. This high proportion reflects the significant impact of international trade on the country's economy. Thus, the share of international trade varies between a minimum of 49.71% and a maximum of 96.10%. These significant fluctuations reflect the variability of Saudi Arabia's dependence on international trade. The standard deviation of 12.04% measures the dispersion of international trade around the mean of 71.27%, indicating significant variation in the level of international trade in Saudi Arabia.

Table 2. Descriptive Statistics

	Mean	Median	Max	Min	Stand.Dev	Observations
ER	0.016774	0.010000	0.060000	0.010000	0.013997	31
DCO2	0.009476	0.016299	0.062792	-0.062962	0.032439	31
DINNOV	0.197487	0.096626	1.111111	-0.394737	0.332317	31
ENR	99.84842	99.99263	99.99678	99.12536	0.287920	31
IT	71.27157	68.16646	96.10264	49.71347	12.03620	31

To capture multicollinearity, we use the correlation matrix in Table 3. It is important to emphasize that considering the correlation coefficients alone is not sufficient to confirm a result. Therefore, this study undertakes a more robust and coherent econometric analysis to corroborate or refute the objectives of this study. A negative correlation between RE and CO2E of -0.27 means that there is an inverse relationship between these two variables. More specifically, a correlation coefficient of -0.27 means that when the amount of renewable energy increases, deviation of CO2 emissions decreases and vice versa. This correlation underscores the importance of policies aimed at promoting renewable energies to achieve CO2 emission reduction targets and to meet international commitments in the fight against climate change. Thus, this correlation can encourage investments in infrastructure and technologies related to renewable energies, which can also stimulate technological innovation in this sector. A very low correlation between RE and DINNOV of -0.029, which suggests that there is little connection between these two variables. In other words, an increase in the share of renewable energy does not strongly correlate with technological innovation in Saudi Arabia. This low correlation shows that other factors can influence the development of innovative technologies in the energy sector, such as government policies, R&D investments, and international partnerships. It highlights the need for policymakers to develop policies that promote sustainable technological innovation while simultaneously reducing CO2 emissions. There is a moderate to strong positive correlation of 0.593 between renewable energy and non-renewable energy. This high correlation suggests that the two energy sources are linked in some way; the use of renewable energy may be associated with an increase in the use of fossil fuels to meet the growing energy demand. Although renewable energy is generally perceived as a cleaner and more sustainable alternative to fossil fuels, its implementation can often be complementary to the use of non-renewable energies. For example, solar and wind, renewable energy sources, can be intermittent, sometimes requiring non-renewable energies to support them during periods of absence. There is a low positive correlation between renewable energy sources (RES) and CO2 emissions of 0.249. This relationship means that when the amount of non-renewable energy increases, there tends to be a slight increase in CO2 emissions and vice versa. This trend reflects the importance given by the country to non-renewable energy sources, where an increase in their use directly leads to an increase in CO2 emissions. International trade and CO2 emissions positively correlate with a coefficient of 0.562, which suggests that higher international trade is associated with an increase in CO2 emissions. This strong positive correlation is explained by Saudi Arabia's dependence on its oil exports for its economy. An increase in international trade could be the result of an increase in oil exports, which could lead to an increase in CO2 emissions due to extraction, refining, and transportation of oil. There is a low positive correlation between IT and DINNOV, with a coefficient of 0.055. A complex relationship is found between international trade and technological innovation. A low positive correlation between IT and RE is 0.193, suggesting that an increase in international trade is associated with an increase in non-renewable energy consumption.

Table 3. Correlation Matrix

	ER	DCO2	DINNOV	ENR	IT
ER	1.000000				
DCO2	-0.272274	1.000000			
DINNOV	-0.029744	0.120655	1.000000		
ENR	0.593263	0.249574	0.095266	1.000000	
IT	-0.444792	0.562518	0.054677	0.193327	1.000000

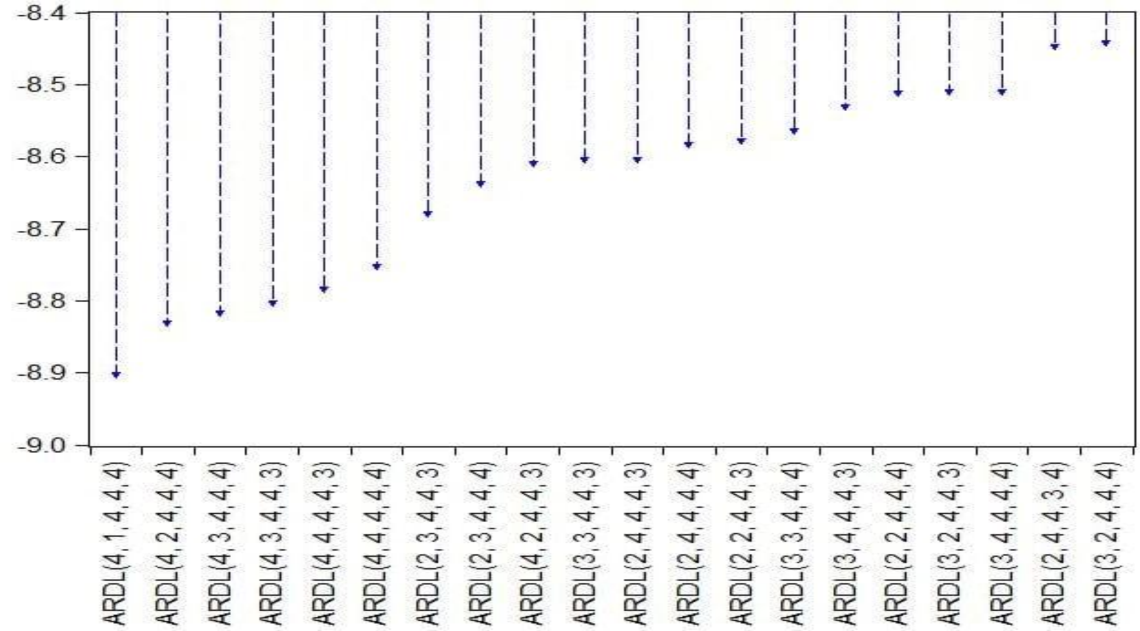
3.3 Tests

3.3.1. Stationarity Test

The Augmented Dickey-Fuller test at level indicates that elasticity is stationary at the 5% level and the ENR variable is stationary at the 1% level. In first difference, we observe that all the variables in our model are stationary at the 1% level. For this, we can estimate our model using the ARDL technique.

Table 4. Results of the unit root test

	ADF Test	
Variable	**At level**	**In Difference 1**
ER	0,8104	0,0000***
DCO2	0,0333**	0,0000***



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4. RESULTS

4.1. ARDL Coefficient

Table 5 below represents the regression using the ARDL method. We will consider the variables of an index (t) to study the instantaneous impact of the exogenous variables on the endogenous variable. Similarly, the variables with an index (t-1) study the short-term impact of the lagged endogenous variable and the exogenous variables on the endogenous variable. The variables with an index of 2 or 3 study the medium-term impact, and finally, the variables with an index of t-4 study the long-term impact. We observe that ER has a significant and positive impact on itself in the short term and long term at the 5% level. On the other hand, there is a non-significant negative impact in the medium term and consequently the absence of an impact in the medium term. The elasticity of CO2 emissions is negatively significant at the 10% level in the short term, whereas there is no short-term impact; conversely, there is no instantaneous impact. The elasticity of innovation has an instantaneous positive impact at the 5% level. However, we observe the absence of an impact in the short and medium term. On the other hand, we observe a significant positive influence at the 5% threshold in the long term. In other words, despite the immediate positive effects of technological innovations, their full impact is manifested in the long term. -RE has an immediate and positive impact at the 1% threshold. Thus, we observe a slight positive impact at the 10% level with a lag of 2 periods. On the other hand, there is a negative and significant impact at the 5% level in the long term. We observe the absence of an impact in the short term and with a lag of 3 years. However, there are positive impacts in the medium term. International trade (IT) shows a significant positive effect, with a one-year lag at the 10% threshold (IT t-1). However, there are no significant immediate, medium, or long-term effects.

Table 5. ARDL Coefficient

Variable	Coefficient	Std. Error	t-Statistic	Prob.
ER (-1)	0.990609	0.261587	3.786914	0.0128 **
ER (-2)	-0.352184	0.450175	-0.782328	0.4694
ER (-3)	-0.681802	0.545147	-1.25112	0.2117

ER (-4)	0.527805	0.193200	2.737176	0.0412 **
DCO2	-0.022076	0.017446	-1.265740	0.5283
DCO2 (-1)	-0.094944	0.037270	-2.545431	0.0516 *
DINNOV	0.019227	0.007495	2.568491	0.0105 **
DINNOV (-1)	0.002600	0.004721	0.550627	0.6030
DINNOV (-2)	-0.004675	0.003716	-1.258969	0.2182
DINNOV (-3)	0.002993	0.004307	0.695123	0.3779
DINNOV (-4)	0.010924	0.002802	3.898062	0.0339 **
ENR	-0.018749	0.003952	-4.727239	0.0050 **
ENR (-1)	-0.009434	0.005938	-1.588753	0.1171
ENR (-2)	0.010020	0.004362	2.297067	0.0735 *
ENR (-3)	0.009438	0.004399	2.145049	0.2088
ENR (-4)	0.022782	0.006740	3.378412	0.0228 **
IT	-0.000184	0.000219	-0.842993	0.4683
IT (-1)	0.000054	0.000199	0.271015	0.7078
IT (-2)	-0.000474	0.000336	-1.410714	0.2270
IT (-3)	0.000101	0.000338	0.298221	0.7621
IT (-4)	-0.000454	0.000331	-1.372925	0.1044
C	3.164060	0.881899	3.587739	0.0157 **

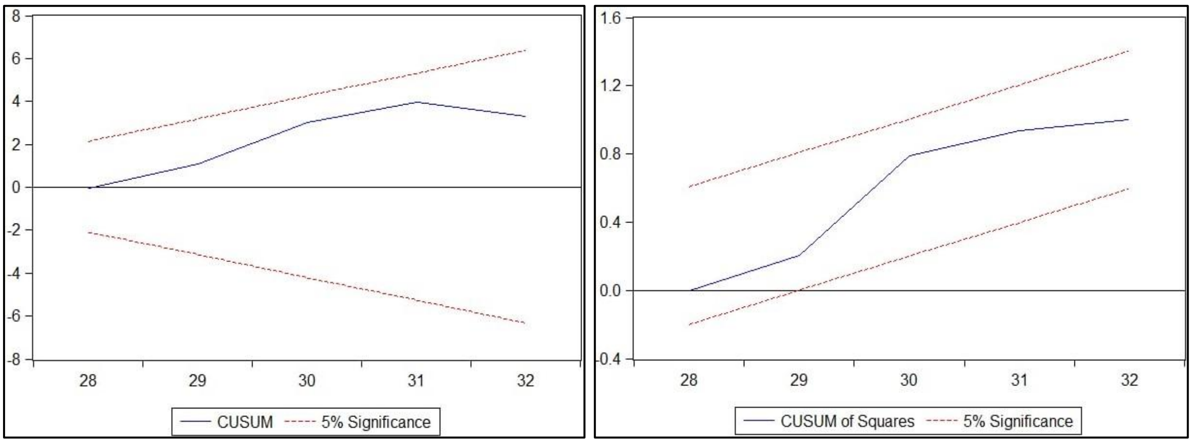
*** significant at the 1% level, ** significant at the 5% level, * significant at the 10% level
Source: authors' estimates

4.2. Robustness Stability Tests

Various testing methods have been used to evaluate the consistency of the ARDL model as well as the reliability of its results. To evaluate the stability of the model, we will use the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests, proposed by Brown et al. (1975). These tests are based on the analysis of the cumulative sum of recursive residuals and the cumulative sum of squares of recursive residuals, with the assumption that the model parameters remain stable when the CUSUM and CUSUMSQ plots respectively stay within the 5% significance level. We will also apply the Breusch-Godfrey LM serial correlation test to examine the presence of autocorrelation, the Breusch-Pagan-Godfrey heteroscedasticity test, and the ARCH test will be used to detect heteroscedasticity.

To examine the hypothesis of long-term stability of the relationships between the estimated variables, the (CUSUM) test is used. To test the stability of the model, the (CUSUM of Squares) test, which is based on the cumulative sum of the squares of recursive residuals, is the most relevant with a null hypothesis of stability of the relationship, between two lines representing the bounds of the interval. These tests offer an effective and sensitive means of monitoring processes and detecting significant changes in the data over time, allowing for proactive management and continuous improvement of processes and performance. According to the results of the CUSUM and CUSUM of Squares tests in Figure 2, we can say that there is no significant structural change in the parameters, and the estimated model appears stable. This observation suggests that the estimated coefficients of the model remain stable over the period from 1992 to 2023, with statistical significance at the 5% level.

Figure 2. CUSUM and CUSUMSQ Tests



According to the findings in Table 6, based on the results of the autocorrelation tests, the probability of the F statistic (0.0140) indicates that autocorrelation of errors is significant. This means that the residuals are correlated over time, which could suggest an omitted dynamic in the model. The probability of the heteroscedasticity test (0.0654) indicates that we cannot reject the null hypothesis of homoscedasticity with a high level of certainty. Furthermore, the probability of this normality test is (0.5400), indicating that the residuals follow a normal distribution, which means that the normality assumptions of the residuals are met.

Table 6. Robustness Test

	F-Statistic	Probability
LM test of error autocorrelation	24.29761	0.0140
Heteroscedasticity test	3.45	0.0654
Normality test	1.23	0.5400

Source: author's estimates

5. CONCLUSION

This study examined the combined impact of international trade and technological innovation on renewable energy consumption in Saudi Arabia over the 1990–2021 period, using an ARDL model-based econometric approach. This approach was preceded by descriptive statistical analyses and a correlation matrix, allowing for the establishment of a robust empirical framework. The results obtained highlight differentiated dynamics in the short and long term, revealing important levers to guide Saudi energy policy towards sustainable development.

It emerges from this analysis that renewable energies consumption exerts a significant and positive effect on itself, both in the short term and in the long term. This result demonstrates the gradual rise of these energy sources, made possible by encouraging policies, tax incentives, and increasing investments in green infrastructure (Al Shammre, 2024). This self-reinforcing dynamic illustrates that the commitments made in the field of renewable energy are beginning to produce lasting effects. Moreover, technological innovation has shown a significant long-term impact, but few immediate or med-term effects. This confirms the idea that gains in energy efficiency and performance follow a logic of slow and progressive technology diffusion, in line with the conclusions of Duyen et al. (2023), Raza et al. (2023), and Jiang et al. (2024), who highlight that the effects of innovation on renewable energy consumption primarily manifest in the long term, through a deep restructuring of the energy system. International trade, on the other hand, exerts a positive effect on the consumption of renewable energies, but with a one-year time lag. This result indicates that trade openness facilitates access to the equipment, technologies, and skills necessary for the energy transition, but that the realization of these benefits requires a period of absorption and adaptation. This finding is in line with the work of Banerjee & Kallal (2022), Abu-Rumman et al. (2020), and Headley & Copp (2020), which show that the effects of trade on renewables are often delayed and linked to a country's ability to integrate imported innovations into its productive fabric. CO_2 emissions also have a significant positive long-term effect, although no immediate effect has been observed. This result, interpreted in light of the efforts to diversify the Saudi economy (Leitao et al., 2022), suggests that environmental pressures can act as a long-term driver of change, indirectly stimulating the adoption of cleaner energy solutions. Another major lesson from this study concerns non-renewable energies. These continue to exert a positive influence on the consumption of renewables in the short term, particularly by providing the financial resources necessary for the initial investment. However, this effect gradually diminishes, revealing that their role in the transition is time-limited. This dynamic highlights the paradox of an energy model where the transition to sustainability still, to some extent, relies on revenues from fossil resources.

The political implications of these results are clear: to succeed in its energy transition, Saudi Arabia will not only need to strengthen its innovation and technological absorption capacities but also support international trade with an appropriate institutional environment and gradually reduce its dependence on fossil fuels. Trade, innovation, and national policies must act in a complementary manner to ensure the effectiveness and sustainability of the process.

However, some limitations must be acknowledged. First, the period covered by the study (1992–2023) does not allow for the integration of the most recent developments in the field of green technologies. Next, the rapid pace of innovations can render the conclusions quickly obsolete if they are not regularly updated. Finally, the scarcity of studies combining the three examined dimensions (trade, innovation, renewable energies) represents a constraint in comparing the results.

This study, focused on Saudi Arabia, thus opens promising perspectives for future research. It would be relevant to extend the analysis to other countries, to include variables such as foreign direct investments (FDI), climate finance flows, or even the segmentation of renewable energies by sector (solar, wind, hydro, biomass). Such approaches would allow for a better understanding of how economic and technological factors interact to stimulate or hinder the energy transition. International comparisons could also offer useful insights for adjusting Saudi public policies, with a view to enhanced sustainable development.

In summary, this study confirms the strategic importance of technological innovation and international trade to promote the consumption of renewable energies, while showing that these levers only fully produce their effects if accompanied by targeted, planned, and coherent long-term policies. In a country like Saudi Arabia, rich in fossil resources but committed to diversifying its economy, the success of this energy transformation relies on a delicate balance between its oil heritage, technological ambition, and commercial openness.

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